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**A MARS RIOMETER
Antenna Considerations**

**FINAL REPORT
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1.0 PROJECT OVERVIEW.

This report describes work accomplished under NASA Grant NAG5-9706, "A Mars Riometer," awarded by NASA's Planetary Instruments Definition and Development Program. The purpose of this project was to define antenna requirements for a Mars radio science instrument, the Relative Ionospheric Opacity Meter (riometer), and to explore design options for deployment of a riometer antenna system on the surface of Mars, or in the near-surface Mars environment.

In our original proposal, we sought to develop a Mars riometer instrument that would more than double the operating frequency range over our present instrument (which is limited to frequencies below 40 MHz). This would allow, for the first time, the continuous measurement of ionospheric absorption over a wide range of causal event energies. Our proposal detailed tasks related to instrument design modifications, and to the development of an effective antenna system. The proposal reviewers noted that "the antenna provides the next major challenge." They expressed concern over the adequacy of an antenna system constrained by the severe size and mass restrictions imposed by Mars surface mission scenarios. They suggested that we address problems of antenna size, stowing and deployment and/or show that sufficient efficiency can be achieved with a smaller antenna. They also recommended that we add a mechanical design aspect to the work effort and an evaluation of the optimum antenna length. In light of the approved funding level of our proposed work (10% of requested), we focused efforts on a practical Mars riometer antenna definition and design, and deployment options.

In this section, we describe riometer operation and radio receiver parameters appropriate for aeronomy investigations. In Section 2 we address antenna requirements to cover the range of frequencies appropriate for Mars riometry. Specific options for practical antenna systems are presented in Section 3, and conclusions are presented in Section 4.

1.1 Background

A number of spacecraft have visited Mars, increasing our knowledge of its atmosphere, ionosphere and solar-wind interactions. However, in spite of data returned from previous missions, we still have not observed key regions of the Martian ionosphere (*Zhang et al.*, 1990a; *Kliore*, 1992). Orbital geometry precludes radio occultation observations of the Martian ionosphere within solar zenith angles of less than 45° (midday) or greater than about 135° (midnight sector). We have limited knowledge of the ionosphere of Mars below the altitude of 100 km (*Zhang et al.*, 1990a, b). This region is where energetic particles are likely deposited (*Vellinov and Mateev*, 1991). Enhanced ionization by interplanetary ions, particularly during solar proton events (SPE) is possible. Because of the lower Martian atmospheric densities, low-energy electrons should penetrate to a greater depth than in the terrestrial atmosphere. Electron precipitation may be responsible for maintaining the nighttime Martian ionosphere (*Verigin et al.*, 1991; *Zhang et al.*, 1990b) and could be an important source of ionization below 100 km (*Detrick et al.*, 1997).

1.2 Ionospheric Absorption.

Radio signals are attenuated as they pass through an ionosphere. Radio waves transfer kinetic energy to ionospheric electrons, which collide with neutrals, extracting energy from the radio wave. Absorption is a function radiowave frequency, and a function of the electron number density and collision frequencies (electron-neutral, electron-ion, and ion-neutral collision) along the signal propagation ray path. On Earth, RF absorption is generally greatest in the D-region. D-region ionization results from several sources: precipitating electrons, solar photoionization, high-energy solar protons and galactic cosmic rays, and meteors. Studies of the temporal variations of absorption, when combined with measurements from other sensors, have provided information on the sources and energy spectra of keV electrons (*Rosenberg and Dudeney, 1986; Stoker, 1987*), and MeV interplanetary ions (*Armstrong, et al., 1989*).

In the Martian atmosphere, the electron-neutral momentum transfer collision frequency (which determines the efficiency for absorbing radio waves in the lower atmosphere) is $\sim 10^{-7} \text{ s}^{-1}$ per molecule CO_2 (*Detrick et al, 1997*). By contrast, the collision frequency is $\sim 2 \times 10^{-9} \text{ s}^{-1}$ per molecule N_2 in the terrestrial atmosphere (*Davies, 1990*). Since the collision frequency in CO_2 is constant below an electron energy of 1 eV (*Hake and Phelps, 1967*), the absorption formula (*Sen and Wyller, 1960*) reduces to the Appleton-Hartree form:

$$A(\text{dB}) = 4.61 \times 10^4 \int ds \frac{n_e(s) \nu(s)}{\nu^2(s) + \omega^2} \quad (1)$$

where ν is the effective collision frequency, ω is the radio frequency, and the integral is along the radio wave path, s .

Absorption efficiency (term in the integral in Equation 1, divided by n_e) is independent of the electron density. The absorption efficiencies of the terrestrial and Martian atmospheres are similar (*Detrick et al. (1997)*). However, the absorption efficiency peaks at higher altitudes on Mars than on Earth, and drops off more slowly with increasing altitude. If Mars has appreciable ionization at 50 to 90 km altitude, HF radiowave absorption will likely be greater in the Martian atmosphere than Earth's, even though the neutral densities in the Martian atmosphere are less than those at comparable altitudes on Earth.

1.3 Riometry.

The riometer measures the signal strength of exo-atmospheric radio sources. For these measurements, radio wave absorption can be determined to study phenomena in the lower ionosphere (in the D and E regions) and also at higher altitudes in auroral latitudes (*Little and Leinbach, 1958, 1959; Fry et al., 2000* and references therein). The instrument measures small variations in electron density at ionospheric heights by determining the absorption in the ionosphere of cosmic radio noise (RF energy emitted from stars in the galaxy) as it passes through the atmosphere.

The riometer consists of an antenna connected to a self-calibrating radio receiver, and it is generally operated at a fixed frequency in the high-HF or low-VHF range. The riometer measures signal strength of the radio sky as it sweeps overhead once per day as the planet rotates. The

instantaneous galactic radio noise strength (the aggregate of all radio sources in the beam pattern) is assumed to remain constant, so changes in received noise from a given portion of the sky indicates ionospheric absorption has attenuated the signal.

At a given local time, decreases in noise from the average or “quiet day” values indicate absorption of the signal by the ionosphere. Absorption is then,

$$A \text{ (dB)} = -10 \log_{10} P/P_0 \quad (2)$$

where P is the measured antenna noise power, and P_0 is the power when no absorption is present.

Calculations of the expected RF absorption provide bounds on the required sensitivity and dynamic range of a riometer instrument. The greater absorption efficiency of the Martian atmosphere, should result in a greater amount of riometer absorption for the same incident particle fluxes (*Detrick et al.*, 1997). The enhanced absorption and lower radio noise levels expected on Mars imply that riometry is very appropriate for Mars aeronomy studies.

Riometers typically operate at radio frequencies above several times the ionospheric critical frequency (peak plasma frequency in the overhead ionosphere). The riometer works better at lower frequencies (absorption increases as the inverse of the frequency squared). However the signal-to-noise ratio decreases at lower frequencies as RF noise is received from over-the-horizon sources. Also, it is desirable to monitor the ionospheric effects of particle deposition during the larger solar energetic proton events, where the riometer signal may be deeply absorbed even at frequencies up to the mid-VHF range.

The riometer antenna, or antennas, must efficiently collect energy at discrete frequencies over the instrument’s operating frequency range. Collection efficiency increases with antenna size. Therefore, for planetary missions, the challenge is to provide an adequate signal-to-noise ratio to the radio receiver across the operating frequency, while minimizing antenna mass and deployment complexity. In the riometry discussion above, a key assumption is that the antenna beam pattern and pointing direction are fixed. Deformation of the antenna or changes in pointing direction (for example by a strong wind) will result in changes in the beam pattern, received signal, and will introduce errors in the derived absorption. Proven antenna designs for terrestrial riometry include the cross-dipole (turnstile), the yagi, and the horizontal loop antenna.

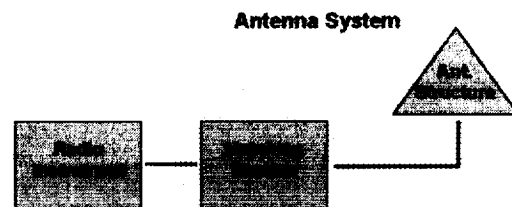
The riometer operates on the principal that cosmic RF noise, originating from radio sources outside the atmosphere, is attenuated upon passing through the atmosphere to the surface. Therefore, the riometer must be deployed at altitudes below the ionosphere in order to capture the RF signal from above after it passes through the absorbing ionosphere. In the case of a Mars mission, this rules out placing the instrument on an orbiting platform. Several surface-based or near-surface platforms might serve as hosts for riometer instruments. These include surface landers (e.g., Viking and Mars Pathfinder) and rovers (surface vehicles, airplanes and balloons). The riometer antenna will have to be mounted on, in, or deployed from, the host platform.

2.0 MARS RIOMETER ANTENNA REQUIREMENTS

Spacecraft observations have shown that typical daytime peak electron densities in the Martian ionosphere are about $1\text{-}2 \times 10^5 \text{ cm}^{-3}$, dropping to about 10^3 cm^{-3} , or less, at night (*Zhang et al.*, 1990a, b). Therefore, ionospheric critical frequencies for radiowave propagation are typically less than 4 MHz in the daytime Martian ionosphere, and several hundred kHz at night (*Fry and Yowell*, 1994). RF signals can propagate over the horizon at frequencies up to several times the critical frequency. In order to minimize possible RF noise propagated from over the horizon, it is desirable to operate a Mars riometer at frequencies above 15-20 MHz (*Fry and Rosenberg*, 1999). Also the antenna gain pattern should be maximum in the vertical direction in order to capture the overhead cosmic radio noise while rejecting spurious noise from sources near the horizon.

Riometry will not be effective above some higher radio frequency because absorption by the Martian atmosphere will become negligible during all but the most intense energetic particle events. Our design work indicates that it is desirable to construct a Mars riometer instrument and antenna that will operate over a frequency range of roughly 20 to 90 MHz.

Figure 1. Riometer system block diagram, showing the radio instrument, and antenna subsystem consisting of the matching section and antenna structure.



2.1 Riometer Antenna Considerations.

Figure 1 is a block diagram of the riometer/antenna signal chain. The antenna subsystem consists of the matching section and antenna. The impedance of the receiver is nominally 50 ohms. The antenna may or may not exhibit the same impedance as the receiver, so a matching section may be inserted to allow the most efficient transfer of the signal from the antenna to the receiver. For a Mars mission, the desirable features of an antenna often compete with each other, so compromises must be made. For example, smaller antenna mass, and therefore smaller size, is desirable, but the collection efficiency of an antenna degrades as size is decreased.

Although imaging riometers are now the state of the art for terrestrial ionospheric investigations (*Detrick and Rosenberg*, 1990), a Mars mission places severe mass, size and power restrictions in the science instrument. Presently only the traditional broadbeam riometer appears practical for a Mars mission. This instrument measures cosmic radio noise integrated over a large portion of the overhead sky. The antenna half-power beam width is nominally 60° .

A desirable broad-beam riometer antenna would be vertically pointing, have a $\frac{1}{2}$ power beam width of about 60° , have minimal mass but adequate gain, and not require additional power to tune over the operating frequency range. In addition, the antenna should be fairly rigid so that the antenna beam pattern remains consistent over the duration of the experiment.

Table 1 summarizes the desirable antenna characteristics for a broadbeam Mars riometer.

Table 1. Desired antenna characteristics for a Mars broadbeam riometer.	
Operating frequency:	Several discrete in the range 20 - 90 MHz
2:1 SWR Bandwidth:	~200 kHz at each operating frequency
Half-power beam width:	~ 60°
Maximum gain:	Vertically directed
Desired mass:	< 1 kg
Matching section power requirement	< 100 mW

Gain and Directivity. Antenna gain and directivity depends upon the shape and electrical properties of the antenna, and conductivity and dielectric properties of the nearby surface material.

Coupling to Radio Instrument. The antenna must be matched to the radio to optimize the transfer of signal between the antenna and the radio, to form the desired gain pattern, or to maximize antenna efficiency. If a single antenna is to be used over the entire proposed frequency range (20-90 MHz), a matching section will likely be necessary.

Size vs. Mass. Antenna efficiency increases with antenna size. On the other hand, there is a need to keep the mass as low as possible. Stowed size should be minimized

Reliable Deployment. Reliability of antenna deployment is an issue as the antenna configuration becomes more complicated. The Mars Pathfinder mission has proven that a rover can maneuver on the surface of Mars, and a rover might be used to deploy the antenna structure.

2.2 Effects of Surface Electrical Characteristics and Consequences.

As on Earth, the effects of an RF-lossy surface material on Mars must be considered in antenna design. This may be less of a problem on a water-free Mars, due to the lower dielectric constant expected on Mars compared to the Earth (*Neilsen*, 1995). However, we cannot assume the Martian crust is dry, even near the surface (*Carr*, 1996). *Grimm* (2001) noted that the frequency-dependent electrical properties of Mars surface materials may vary over a wide range depending upon the surface material properties and the presence of dissolved solids in any subsurface groundwater.

Riometers work well on Earth, in spite of the often large variations in ground properties with seasonal changes. In fact, an imaging riometer array in Antarctica performed very well even though it was eventually completely buried in snow (*Rose et al.*, 2000). The effect of the difference in dielectric constant of the snow compared to air was taken into consideration in the design of the array. Therefore, the antenna performance improved as the snow gradually covered the array. Notably, the attenuation of radio signal strength per meter for Antarctic snow at 38.2 MHz was found to be negligible (~ 0.013 dB/m).

3.0 PRACTICAL MARS RIOMETER ANTENNAS AND PLATFORMS

In this section, we discuss several riometer antennas and deployment options for specific platforms: a Mars lander and a balloon aerobot. An airplane platform presently does not appear suitable for riometry, as discussed below.

For the radio frequency range of our riometer instrument (20-90 MHz), the required dimensions of the antenna are on the order of 1.5 to 8 meters. An antenna optimized for the lowest frequency (20 MHz) will be largest in terms of physical dimensions and mass, and will be the most difficult to deploy. Therefore, we use the 20 MHz antenna in our design scenarios in this discussion.

3.1 Riometer Antennas

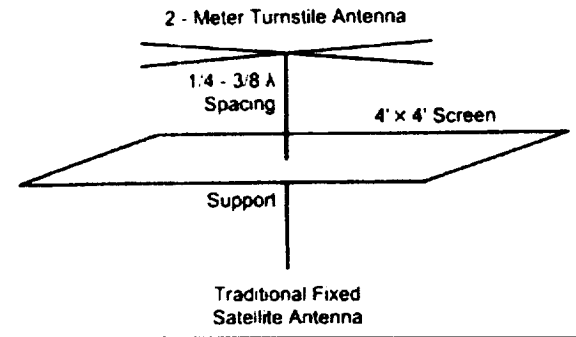
The following antennas are used in terrestrial riometry: turnstiles, yagis, and horizontal loop antennas. We looked at these and also considered several newer antenna designs including the flag/pennant antenna (*Cunningham*, 2000) and the Moxon antenna (*Moxon*, 1982; *Cebik*, 2000, 2001). The Numerical Electromagnetic Code version 3 (NEC-2) modeling software (e.g., *Hubing*, 1991) with the EZNEC commercial interface (*Lewellen*, 2000) was used to analyze candidate antenna characteristics. Table 2 summarizes characteristics of these antennas.

Table 2. Candidate antennas for a Mars Riometer.

	Turnstile	Loop yagi	Pennant/Flag	Moxon
Dimensions:	1.5 - 8 m tip-to-tip	circular, 1-5 m	1-4 m	square, 4x4 m
Mass:	1-2 kg	< 1 kg	< 1 kg	< 1 kg
Deployment:	mechanical or balloon	balloon envelope	balloon envelope	mechanical or balloon

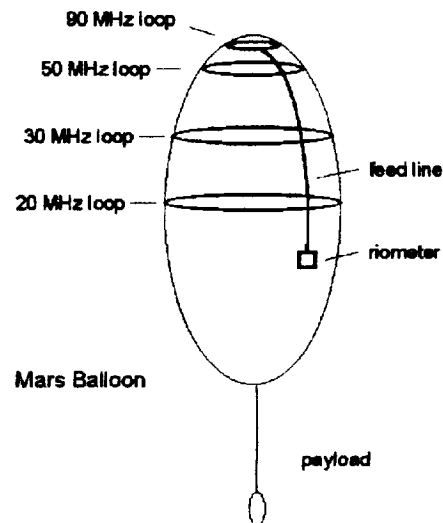
Turnstile. Figure 2, from *Cebik* (2001) shows the configuration of the ground-plane turnstile antenna. The turnstile consists of horizontal center-fed dipoles fed 90° out of phase, over a ground plane or reflector elements. The dipoles are typically located between $.2$ and $.5 \lambda$ above the ground plane/reflector. The 2-element crossed yagi is a essentially a turnstile antenna over a pair of orthogonal reflector elements.

Figure 2. Construction of the ground-plane turnstile antenna. This figure is from *Cebik*, 2001. The antenna beam pattern is shown in Figure 5, below, compared with the pattern of the Moxon antenna.



Loop/Loop-Yagi. The loop-yagi, or quad antenna shows increased gain over a linear yagi with the same number of elements. The antenna elements are often constructed of wire and non-metallic separators to maintain the antenna configuration. A balloon envelope could also serve to maintain the antenna's shape. Figure 3 is a conceptual diagram of a balloon-borne riometer and multi-loop antenna system. Four separate resonant loop antennas are coupled to the receiver to cover four discrete frequency channels (20, 30, 50, and 90 MHz). Maximum gain is along the balloon's vertical axis. Alternately, the antenna could be configured as a log-periodic loop antenna to cover a continuous range of frequencies, or as a multi-element loop yagi optimized for one frequency channel.

Figure 3. Conceptual diagram of a balloon-borne riometer and antenna system consisting of four separate resonant loop antennas. Balloon diameter is approximately 16 meters. The riometer instrument may be attached to the balloon fabric or located in the payload section of the aerobot.



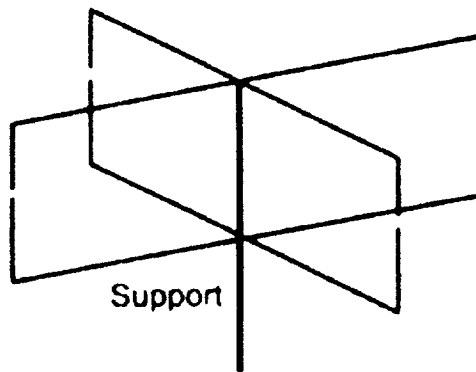
Pennant/Flag. *Cunningham* (2000) described the performance of a broadband receiving antenna that works well even near poor ground. This antenna consists of a triangular, diamond, or rectangular wire loop fed at one end and terminated by a matching resistor at the other end. The physical dimensions of the pennant/flag are small, generally less than a wavelength. The maximum gain of these antennas is on the order of -30 dB, but they exhibit a very high front-to-back ratio (-15 to -60 dB) over a wide frequency range. The strong attenuation of the received

signal can be compensated for by preamplification. Care should be taken to shield the feedline with a good matching transformer.

Moxon. The Moxon antenna (*Moxon*, 1982) has experienced recent interest in the communications community because it is physically smaller than an equivalent yagi antenna, it has a nominal 50 ohm feed-point impedance when operated at its resonance frequency (eliminating the need for a matching section), and it exhibits a very high front-to-back gain ratio (*Cebik*, 2000). A variation of the Moxon developed for satellite communications is the vertically directed Moxon pair (*Cebik*, 2001), shown in Figure 4.

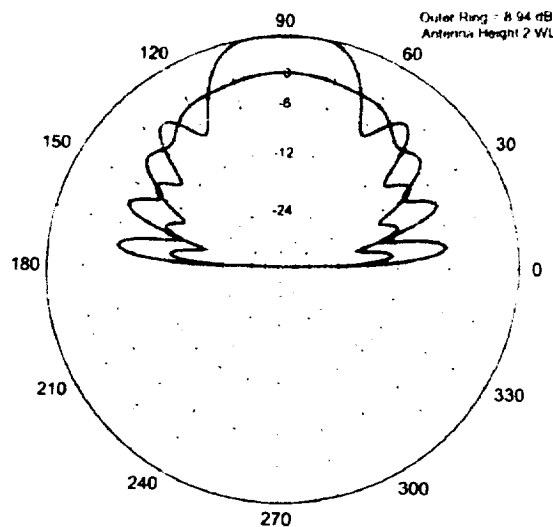
Figure 4. Construction of the orthogonal Moxon pair antenna. This figure is from *Cebik* (2001). This antenna could also be supported inside the envelope of a Mars balloon, or deployed from a lander.

Dual "Turnstile" Moxon Rectangle



Simpler Improved Fixed Satellite Antenna

Figure 5. Comparison of antenna beam patterns in the vertical plane for the 2 element turnstile (crossed 2-element yagis) shown in the blue curve, and the orthogonal Moxon pair shown in red. This figure is from *Cebik* (2001).



The antenna beam patterns of the 2-element yagi (blue curve) and the crossed Moxon antenna pair (red curve) are shown in Figure 5 (also from *Cebik*, 2001). Both antennas are located at a height of 2λ above ground.

3.2 Platforms

Landers. The riometer antenna could be built into the mechanical design of a Mars surface lander. For example, a turnstile antenna might consist of horizontal masts, deployed after landing. There are several space-proven designs for deployable structures. Notable among these are the *STEM* (Storable Tubular Extendible Member) and AstroMast, both developed by AeroAstro Corporation (Carpinteria, CA). The STEM devices were used in the Mars Pathfinder rover ramp. They stow in very small volumes and deploy as long cylindrical tubes, providing an actuation force in the process. Variations of the simple STEM include the BI-STEM and Interlocking BI-STEM designs for improved mechanical properties. As examples, the Model A-204 Tip Drum STEM antenna is self-extends up to 18 meters long, yet its stowed volume is 10.7 x 6.4 x 6.4 cm and its mass is 0.57 Kg. Another device, the Jack-in-the-Box (JIB), deploys to a length of 3 meters using its own stored spring energy. The JIB mass is approximately 250 gm (AeroAstro marketing material, 1997).

The AstroMast provides deployable masts up to 18 meters long. Improved rigidity comes at a higher cost in required mass over the STEM. AstroMasts have been employed on a number of space missions, including Voyager, GOES, Milstar, and DMSP. Astromasts are small when stowed, and deployed lengths are approximately fifty times stowed lengths.

Rover deployed. A Mars rover vehicle could deploy a loop or crossed dipole wire antenna by laying it out directly on the Mars surface regolith. However, surface properties might degrade antenna performance unless the antenna is deployed over a thick layer of snow or ice. Amateur radio operators often successfully use antennas that are in direct contact with extremely dry or frozen surfaces. Our modeling indicates this may work well if the frost line is deeper than about a tenth of a wavelength. As mentioned above, an imaging riometer system performed successfully with the antenna array completely buried in the Antarctic snow.

Balloons. Because the electrical properties of the landing site are generally unknown in advance, it is difficult to predict the shape of the beam pattern when the antenna is deployed at Mars. One straightforward way to avoid this issue is to loft the riometer instrument and antenna in a balloon aerobot. A balloon platform might easily accommodate a wire or foil-strip antenna in the balloon fabric (See Figure 3, and, for example, *Grimm*, 2001, Figure 16). As the balloon flies to some altitude and performs its mission, it removes the antenna from the unknown surface to some distance. At higher altitudes, the antenna beam pattern eventually approaches its free-space geometry, which can be easily modeled. The balloon option is attractive because the antenna could be “self deployed” as the balloon inflates to its final configuration. Antennas that could be incorporated as an integral part of a balloon envelope, or carried by a balloon, include all the designs mentioned above. Separate antennas could be switched in and out of the signal path to cover discrete frequencies over the operating range of the riometer instrument. This would allow a consistent sky viewing geometry at each frequency.

Airplanes. We have looked at airplane missions, but present mission scenarios do not look promising for riometry. Several of the proposed airplane platforms may be large enough to support an antenna, but the missions will last for tens of minutes to several days at most (*W. Calvin*, private communication, 2001). A practical riometer experiment should run for many sols

(Martian days) in order to determine the quiet-day noise curves necessary for establishing absorption levels. Also, the airplanes must travel at high speeds to remain aloft in the thin Martian atmosphere, and it is unlikely any ride-along antenna (or the airplane for that matter) would survive the eventual “landing.”

3.3 Matching Network.

Riometers are traditionally designed to operate with an antenna system having a 50 ohm impedance. Used in a broadband application, it is desirable to use a matching network between the antenna and riometer in order to optimize the signal transfer from the antenna to the receiver. For example, a frequency-adjustable turnstile antenna system would consist of a crossed dipole design having an adjustable matching network located within the central support structure. The riometer would have the capability of relaying commands from the receiver processing unit contained in a Field-Programmable-Gate-Array (FPGA) to the matching network co-located at the antenna. The network would be adjusted by switching in different values of inductors and capacitors. A recipe for the correct values would be contained in the FPGA processor.

Inside the remote matching network, the decoded commands select the component values through the operation of GaAs switches. These devices operate at near zero bias currents, permitting the entire matching network to be very low power. A balun for transforming the unbalanced coaxial cable from the receiver to the balanced antenna connection would also be contained inside a central housing.

A significant number of sub-systems might be implemented on a FPGA. Commands relayed to the matching network will be multiplexed on the antenna input connector. This approach would eliminate the need for any clock oscillators within the matching network. As a result, there should not be a problem with locally generated EMI within the communication portion of the network.

4.0 CONCLUSIONS

We investigated several practical riometer antenna designs for Mars landers and aerobots (balloons). We considered trade-offs between antenna efficiency and practical considerations of deployment, size, mass and power requirements. Although rigid antenna configurations are highly desirable, our design goal was to limit the overall antenna mass to 1 to 2 kg. Several deployable structures are commercially available to meet this goal. In addition, acceptable wire or metallic tape antennas can be incorporated into balloon designs. We presented four classes of antennas that exhibit some gain in the vertical direction to enable the measurement of cosmic radio noise for riometry on Mars. For antenna systems requiring active tuning, the antenna-matching network would likely consume some power when operating. We sought to limit the maximum power draw to <100 mw in active tuning/matching mode, and < 1 mw in fixed-frequency or standby mode. A field-programmable gate array controller could operate within these power margins.

Riometry is one of the simpler techniques for studying the Martian ionosphere from below. Our analyses indicate that a number of riometer antenna designs are practical for Mars missions.

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13. ABSTRACT (Maximum 200 words) This is the final report on NASA Grant NAG5-9706. This project explored riometer (relative ionospheric opacity meter) antenna designs that would be practical for a Mars surface or balloon mission. The riometer is an important radio science instrument for terrestrial aeronomy investigations. The riometer measures absorption of cosmic radio waves by the overhead ionosphere. Studies have shown the instrument should work well on Mars, which has an appreciable daytime ionosphere. There has been concern that the required radio receiver antenna (with possibly a 10 meter scale size) would be too large or too difficult to deploy on Mars. This study addresses those concerns and presents several antenna designs and deployment options. It is found that a Mars balloon would provide an excellent platform for the riometer antenna. The antenna can be incorporated into the envelope design, allowing self-deployment of the antenna as the balloon inflates.				
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